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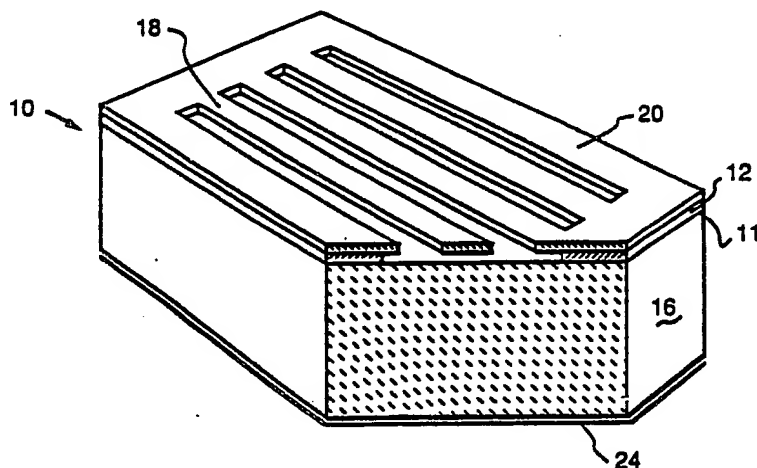
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(54) Title: MODULATING A LIGHT BEAM



(57) Abstract

A modulator (10) for modulating incident rays of light, the modulator having several equally spaced beam elements (18), each having a light reflective planar surface. The beam elements are arranged and supported (12) parallel to each other, with their reflective surfaces parallel. During operation, the elements remain parallel, but the modulator moves the beams so that the perpendicular spacing of their reflective surfaces changes between two configurations. In both configurations, the spacing equals  $m/4$  times the wavelength of incident light. In the first configuration,  $m$  equals an even whole number or zero, and the modulator acts to reflect the incident rays of light as a plane mirror. In the second configuration,  $m$  equals an odd number and the modulator diffracts the incident rays as they are reflected.

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**A. CLASSIFICATION OF SUBJECT MATTER**

IPC(5) : G02B 5/18, 26/00

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According to International Patent Classification (IPC) or to both national classification and IPC

**B. FIELDS SEARCHED**

Minimum documentation searched (classification system followed by classification symbols)

U.S. : 359/566,572,573,291 359/231,295,298,299,302,558,569

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

Please See Extra Sheet.

**C. DOCUMENTS CONSIDERED TO BE RELEVANT**

| Category* | Citation of document, with indication, where appropriate, of the relevant passages                | Relevant to claim No. |
|-----------|---|-----------------------|
| X         | US,A, 4,596,992 (Hornbeck) 24 June 1986 See col. 7, lines 40+ and col. 8, lines 33+ see Fig. 12C. | 1,2,6-8,22<br>23      |
| X         | US,A, 4,492,435 (Banton et al.) 08 January 1985 See Fig. 5.                                       | 11,12                 |



Further documents are listed in the continuation of Box C.



See patent family annex.

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INTERNATIONAL SEARCH REPORT

International application No.

PCT/US93/03939

B. FIELDS SEARCHED

Electronic data bases consulted (Name of data base and where practicable terms used):

APS Diffract()

Reflect()

Grating Phase Grating

Electrostatic Deform()

Quarter Wave

Specification

MODULATING A LIGHT BEAM

BACKGROUND OF THE INVENTION

Field of the Invention

This invention relates to a method and apparatus for modulating a light beam and more particularly to the use of a reflective, deformable diffraction grating for performing such modulation.

Brief Description of the Prior Art

Devices which modulate a light beam, e.g. by altering the amplitude, frequency or phase of the light, find a number of applications. An example of such a device is a spatial light modulator (SLM) which is an electronically or optically controlled device which consists of one or two-dimensional reconfigurable patterns of pixel elements, each of which can individually modulate the amplitude, phase or polarization of an optical wavefront.

These devices have been extensively developed, particularly for applications in the areas of optical processing and computing. They can perform a variety of functions such as: analog multiplication and addition, signal conversion (electrical-to-optical, incoherent-to-coherent, amplification, etc.), nonlinear operations and short term storage. Utilizing these functions, SLMs have seen many different applications from display technology to optical signal processing. For example, SLMs have been used as optical correlators (e.g., pattern recognition devices, programmable holograms), optical matrix processors (e.g., matrix multipliers, optical cross-bar switches with broadcast capabilities, optical neural networks, radar beam forming), digital optical architectures (e.g., highly parallel optical computers) and displays.

The requirements for SLM technology depend strongly on the application in mind: for example, a display requires low bandwidth but a high dynamic range while

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1 optical computers benefit from high response times but  
2 don't require such high dynamic ranges. Generally,  
3 systems designers require SLMs with characteristics such  
4 as: high resolution, high speed (kHz frame rates), good  
5 gray scale high contrast ratio or modulation depth,  
6 optical flatness, VLSI compatible, easy handling  
7 capability and low cost. To date, no one SLM design can  
8 satisfy all the above requirements. As a result,  
9 different types of SLMs have been developed for different  
10 applications, often resulting in trade-offs.

11 Texas Instrument, for instance, has developed a  
12 "Deformable Mirror Device (DMD)" that utilizes an  
13 electromechanical means of deflecting an optical beam.  
14 The mechanical motions needed for the operation of the DMD  
15 are relatively large and, as a result, the bandwidths are  
16 limited to tens of kilohertz. This device, however, gives  
17 good contrast ratios and high-resolution and is,  
18 furthermore, compatible with CMOS, and other low power  
19 technologies.

20 Nematic and ferroelectric liquid crystals have also  
21 been used as the active layer in several SLMs. Since the  
22 electrooptic effect in liquid crystals is based on the  
23 mechanical reorientation of molecular dipoles, it is to be  
24 expected that liquid crystals are faster than the DMD-type  
25 devices. Modulators using ferroelectric liquid crystals  
26 have exhibited moderate switching speeds (150  $\mu$ sec to 100  
27 nsec), low-power consumption, VLSI compatible switching  
28 voltages (5-10 V), high extinction ratios, high resolution  
29 and large apertures. However, these devices suffer from  
30 the drawbacks of limited liquid crystal lifetimes and  
31 operating temperature ranges. In addition, the  
32 manufacturing process is complicated by alignment problems  
33 and film thickness uniformity issues.

34 Magneto optic modulation schemes have been used to  
35 achieve faster switching speeds and to provide an optical  
36 pattern memory cell. Although these devices, in addition  
37 to achieving fast switching speeds, can achieve large  
38 contrast ratios, they suffer from a low (<10%) throughput

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1 efficiency and are, therefore, often unsuitable for many  
2 applications.

3 The need is therefore for a light modulation device  
4 which overcomes these drawbacks.

5 Beside SLMs, another area of use of light modulators  
6 is in fiber optics. Fiber optic modulators are  
7 electronically controlled devices that modulate light  
8 intensity and are designed to be compatible with optical  
9 fibers. For high speed communication applications,  
10 lithium niobate ( $\text{LiNbO}_3$ ) traveling wave modulators  
11 represent the state-of-the-art, but there is a need for  
12 low power, high efficiency, low loss, inexpensive fiber  
13 optic modulators, that can be integrated with silicon  
14 sensors and electronics, for data acquisition and medical  
15 applications. A typical use of a modulator combined  
16 with fiber optic technology, for example, is a data  
17 acquisition system on an airplane which consists of a  
18 central data processing unit that gathers data from remote  
19 sensors. Because of their lightweight and electro-  
20 magnetic immunity characteristics, fiber optics provide an  
21 ideal communication medium between the processor and the  
22 sensors which produce an electrical output that must be  
23 converted to an optical signal for transmission. The most  
24 efficient way to do this is to have a continuous wave  
25 laser at the processor and a modulator operating in  
26 reflection at the sensor. In this configuration, it is  
27 also possible to deliver power to the sensor over the  
28 fiber.

29 In this type of application the modulator should  
30 operate with high contrast and low insertion loss to  
31 maximize the signal to noise ratio and have low power  
32 consumption. It should further be compatible with silicon  
33 technology because the sensors and signal conditioning  
34 electronics used in these systems are largely implemented  
35 in silicon.

36 Another use of a modulator combined with fiber optic  
37 technology is in the monitoring of sensors that are  
38 surgically implanted in the human body. Here optical  
39 fibers are preferred to electrical cables because of their

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1 galvanic isolation, and any modulator used in these  
2 applications should exhibit high contrast combined with  
3 low insertion loss because of signal to noise  
4 considerations. Furthermore, as size is important in  
5 implanted devices, the modulator must be integratable with  
6 silicon sensors and electronics.

7 There exist no prior art devices that have the  
8 characteristics enumerated above. Modulators based on the  
9 electro-optic, Franz-Keldysh, Quantum-Confined-Stark or  
10 Wannier-Stark effect in III-V semiconductors have high  
11 contrast and low insertion loss, but are expensive and not  
12 compatible with silicon devices. Waveguide modulators  
13 employing glass or epi-layers on silicon, require too much  
14 area and too complex fabrication to be easily integratable  
15 with other silicon devices. Silicon modulators that do  
16 not employ waveguides and that are based on the plasma  
17 effect, require high electrical drive power and do not  
18 achieve high contrast.

19 The need is therefore for a light modulator which can  
20 be used with fiber optic technology with low power, high  
21 efficiency, low loss, low cost and compatibility with  
22 multimode optical fibers and silicon technology.

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SUMMARY OF THE INVENTION

Objects of the Invention

Accordingly, it is an object of this invention to provide a light modulator which alone or together with other modulators exhibits most of the following characteristics: high resolution, high speed (Khz frame rates), gray levels (100 levels), high contrast ratio or modulation depth, optical flatness, VLSI compatible, easy handling capability and low cost.

A further object of this invention is to provide a light modulator which has a tolerance for high optical power and good optical throughput.

Yet another object of this invention is to provide a light modulator which is compatible with CMOS technology.

Still another object of this invention is to provide a light modulator capable of use with fiber optic technology.

A final object of this invention is to provide a light modulator which is capable of modulating white light to produce colored light.

Summary

Briefly a presently preferred embodiment of this invention includes a modulator for modulating incident rays of light, the modulator comprising a plurality of equally spaced apart beam elements, each of which includes a light reflective planar surface. The elements are arranged parallel to each other with their light reflective surfaces parallel to each other. The modulator includes means for supporting the beam elements in relation to one another and means for moving the beam elements relative to one another so that the beams move between a first configuration wherein the modulator acts to reflect the incident rays of light as a plane mirror, and a second configuration wherein the modulator diffracts the incident rays of light as they are reflected therefrom. In operation, the light reflective surfaces of

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1 the beam elements remain parallel to each other in both  
2 the first and the second configurations and the  
3 perpendicular spacing between the reflective surfaces of  
4 adjacent beam elements is equal to  $m/4$  times the  
5 wavelength of the incident rays of light, wherein  $m$  = an  
6 even whole number or zero when the beam elements are in  
7 the first configuration and  $m$  = an odd number when the  
8 beam elements are in the second configuration.

9 One embodiment of this invention includes a  
10 reflective deformable grating light modulator, with a  
11 grating amplitude that can be controlled electronically,  
12 consisting of a reflective substrate with a deformable  
13 grating suspended above it. In its undeformed state, with  
14 no voltage applied between the elements of the grating and  
15 the substrate, the grating amplitude is one half of the  
16 wavelength of the incoming light. Since the round-trip  
17 path difference between the light reflected from the top  
18 and bottom of the grating is one wavelength, no  
19 diffraction occurs. When a voltage is applied between the  
20 grating elements and the substrate, the electrostatic  
21 force pulls the elements down to cause the grating  
22 amplitude to become one quarter of the wavelength so that  
23 reflections from the elements and the substrate add  
24 destructively, causing the light to be diffracted. If the  
25 detection system for the reflected light has a numerical  
26 aperture which accepts only the zero order beam, a  
27 mechanical motion of only one quarter of a wavelength is  
28 sufficient to modulate the reflected light with high  
29 contrast.

30 Typically the grating is formed by lithographically  
31 etching a film made of silicon nitride, aluminum, silicon  
32 dioxide or any other material which can be  
33 lithographically etched.

34 The deformable grating modulator of this invention  
35 has the advantage that it is implemented in silicon  
36 technology, using micromachining and sacrificial etching  
37 of thin films to fabricate the gratings. Circuitry for  
38 addressing and multiplexing can be manufactured on the  
39 same silicon substrate and thus be directly integrated

1 with the modulator. Direct integration with electronics  
2 is an important advantage over non-silicon based  
3 technologies like liquid crystal and electrooptic SLMs.  
4 Moreover, the device demonstrates simplicity of  
5 fabrication and can be manufactured with only a few  
6 lithographic steps.

7 A further advantage of the deformable grating  
8 modulator is that because the deformable grating modulator  
9 utilizes diffraction rather than deflection of a light  
10 beam, the required mechanical motions are reduced from  
11 several microns (as in deformable mirror devices) to  
12 tenths of a micron, thus allowing for a potential three  
13 orders of magnitude in increase in speed. This speed is  
14 comparable to the fastest liquid crystal modulators, but  
15 without the device suffering the same complexity in the  
16 manufacturing process.

17 Still a further advantage of these devices is that  
18 the required motion of the grating elements is only one  
19 quarter of a wavelength, which means that elements with  
20 high resonance frequencies can be used.

21 These and other objects and advantages of the present  
22 invention will no doubt become apparent to those skilled  
23 in the art after having read the following detailed  
24 description of the preferred embodiment which is  
25 illustrated in the several figures of the drawing.

26  
27 IN THE DRAWING

28 This invention will now be further illustrated with  
29 reference to the accompanying drawing in which:

30 FIG. 1(a)-(d) are cross-sections through a silicon  
31 substrate illustrating the manufacturing process of a  
32 reflective, deformable diffraction grating according to  
33 one embodiment of the invention;

34 FIG. 2 is an isometric, partially cut-away view of  
35 the diffraction grating, the manufacture of which is  
36 illustrated in FIG. 1.

37 FIG. 3 illustrates the operation of the grating of  
38 FIG. 2 in its "non-defracting" mode;

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FIG. 4 and illustrates the operation of the grating of FIG. 3 in its "diffracting" mode;

FIG. 5 is a cross-section similar to that in FIG. 3, illustrating an alternative embodiment of the grating in its "non-defracting" mode;

FIG. 6 is a cross-section similar to that in FIG. 4, illustrating the grating in FIG. 8 in its "defracting" mode;

FIG. 7 is a pictorial view illustrating a further embodiment of the grating;

FIG. 8 is a cross-section along line 8-8 in FIG. 7;

FIG. 9 is a graphical representation of the modulation of a laser beam by the grating of the invention;

FIG. 10 is an illustration of how the diffraction grating of the invention can be combined with other gratings to form a complex modulator; and

FIG. 11 illustrates the operation of the grating in the modulation of colored light.

#### DESCRIPTION OF PREFERRED EMBODIMENTS

The fabrication steps required to produce a reflective deformable grating 10 according to this invention are illustrated in FIG. 1(a)-(d).

The first step, as illustrated in FIG. 1(a), is the deposition of an insulating layer 11 made of stoichiometric silicon nitride topped with a buffer layer of silicon dioxide followed by the deposition of a sacrificial silicon dioxide film 12 and a low-stress silicon nitride film 14, both 213 nm thick, on a silicon substrate 16. The low-stress silicon nitride film 14 is achieved by incorporating extra silicon (beyond the stoichiometric balance) into the film, during the deposition process. This reduces the tensile stress in the silicon nitride film to roughly 200 MPa.

In the second step, which is illustrated in FIG. 1(b), the silicon nitride film 14 is lithographically patterned into a grid of grating elements in the form of elongate beams 18. In an individual grating, all the

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1 beams are of the same dimension and are arranged parallel  
2 to one another with the spacing between adjacent beams  
3 equal to the beam width. Depending on the design of the  
4 grating, however, beams could typically be 1, 1.5 or 2 $\mu$ m  
5 wide with a length that ranges from 10 $\mu$ m to 120 $\mu$ m. After  
6 this lithographic patterning process a peripheral silicon  
7 nitride frame 20 remains around the entire perimeter of  
8 the upper surface of the silicon substrate 16. This frame  
9 20 is further illustrated in FIG. 2 and will be more fully  
10 described below with reference to that figure.

11 After the patterning process of the second step, the  
12 sacrificial silicon dioxide film 12 is etched in  
13 hydrofluoric acid, resulting in the configuration  
14 illustrated in FIG. 1(c). It can be seen that each beam  
15 18 now forms a free standing silicon nitride bridge, 213  
16 nm thick, which is suspended a distance of 213nm (this  
17 being the thickness of the etched away sacrificial film  
18 12) clear of the silicon substrate. As can further be  
19 seen from this figure the silicon dioxide film 12 is not  
20 entirely etched away below the frame 20 and so the frame  
21 20 is supported, a distance of 213 nm, above the silicon  
22 substrate 16 by this remaining portion of the silicon  
23 dioxide film 12. The beams 18 are stretched within the  
24 frame and kept straight by the tensile stress imparted to  
25 the silicon nitride film 14 during the deposition of that  
26 film.

27 The last fabrication step, illustrated in FIG. 1(d),  
28 is sputtering, through a stencil mask, of a 50 nm thick  
29 aluminum film 22 to enhance the reflectance of both the  
30 beams 18 and the substrate 16 and to provide a first  
31 electrode for applying a voltage between the beams and the  
32 substrate. A second electrode is formed by sputtering an  
33 aluminum film 24, of similar thickness, onto the base of  
34 the silicon substrate 16.

35 The final configuration of the grating is illustrated  
36 in FIG. 2. Here it can be seen that the beams 18 together  
37 with the frame 20 define a grating which, as will be later  
38 explained, can be used for modulating a light beam.  
39 Furthermore, and as can be gathered from the above

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1 described manufacturing process, the frame is formed  
2 integrally with the beams 18 and thus provides a  
3 relatively rigid supporting structure which maintains the  
4 tensile stress within the beams 18. In so doing, and as  
5 the frame 20 is supported by the remainder of the silicon  
6 dioxide film 12 that was not etched away, the beams are  
7 kept straight and a distance of 213 nm above the surface  
8 of the silicon substrate 16.

9 The operation of the deformable grating 10, formed by  
10 the above process, is illustrated with reference to FIG.  
11 3 and 4. Before commencing the description of how the  
12 grating operates, however, it should be recalled that, in  
13 this case, each of the beams 18 are 213 nm thick and are  
14 suspended a distance of 213 nm clear of the substrate 16.  
15 This means that the distance from the top of each beam to  
16 the top of the substrate is 426 nm. Similarly, the  
17 distance between the top of the reflective surface on the  
18 beams to the top of the reflective surface on the  
19 substrate is also 426 nm. This distance is known as the  
20 grating amplitude.

21 In FIG. 3 the grating 10 is shown with no voltage  
22 applied between the substrate 16 and the individual beams  
23 18 and with a lightwave, generally indicated as 26, of a  
24 wavelength  $\lambda = 852$  nm is incident upon the it. The  
25 grating amplitude of 426 nm is therefore equal to half of  
26 the wavelength of the incident light and, therefore, the  
27 total path length difference for the light reflected from  
28 the beams and from the substrate equals the wavelength of  
29 the incident light. As a result, light reflected from the  
30 beams and from the substrate add in phase and the grating  
31 10 acts to reflect the light as a flat mirror.

32 However, as illustrated in FIG. 4, when a voltage is  
33 applied between the beams 18 and the substrate 16 the  
34 electrostatic forces pull the beams 18 down onto the  
35 substrate 16, with the result that the distance between  
36 the top of the beams and the top of the substrate is now  
37 213 nm. As this is one quarter of the wavelength of the  
38 incident lights, The total path length difference for the  
39 light reflected from the beams and from the substrate is

1 now one half of the wavelength (426 nm) of the incident  
2 light and the reflections interfere destructively, causing  
3 the light to be diffracted, indicated as 28.

4 Thus, if this grating is used in combination with a  
5 system, for detecting the reflected light, which has a  
6 numerical aperture sized to detect one order of diffracted  
7 light from the grating e.g., the zero order, this grating  
8 can be used to modulate the reflected light with high  
9 contrast.

10 In FIGS. 5 and 6 an alternative embodiment of the  
11 diffraction grating 30 of the invention is illustrated.  
12 In this embodiment the grating 30 consists of a plurality  
13 of equally spaced, equally sized, fixed beams 32 and a  
14 plurality of equally spaced, equally sized, movable beams  
15 34 in which the movable beams 34 lie in the spaces between  
16 the fixed beams 32. Each fixed beam 32 is supported on  
17 and held in position by a body of supporting material 36  
18 which runs the entire length of the fixed beam 32. The  
19 bodies of material 36 are formed during a lithographic  
20 etching process in which the material between the bodies  
21 36 is removed.

22 As can be seen from FIG. 5 the fixed beams 32 are  
23 arranged to be coplanar with the movable beams 34 and  
24 present a flat upper surface which is coated with a  
25 reflective layer 38. As such the grating 30 acts as a  
26 flat mirror when it reflects incident light, however, when  
27 a voltage is applied between the beams and an electrode 40  
28 at the base of the grating 30 the movable beams 34 move  
29 downwards as is illustrated in FIG. 6. By applying  
30 different voltages the resultant forces on the beams 34  
31 and, therefore, the amount of deflection of the movable  
32 beams 34 can be varied. Accordingly, when the grating  
33 amplitude (defined as the perpendicular distance  $d$  between  
34 the reflective layers 38 on adjacent beams) is  $m/4$  times  
35 the wavelength of the light incident on the grating 30,  
36 the grating 30 will act as a plane mirror when  $m = 0, 2,$   
37  $4...$  (i.e. an even number or zero) and as a reflecting  
38 diffraction grating when  $m = 1, 3, 5...$  (i.e. an odd  
39 number). In this manner the grating 30 can operate to

1 modulate incident light in the same manner as the grating  
2 10 illustrated in FIGS. 1 to 4.

3 Yet another embodiment of the diffraction grating of  
4 the invention is illustrated in FIGS. 7 and 8. As with  
5 the grating 10 in FIGS. 1 to 4 this grating 41 consists of  
6 a sacrificial silicon dioxide film 42, a silicon nitride  
7 film 44 and a substrate 46. In this embodiment, however,  
8 the substrate 46 has no reflective layer formed thereon  
9 and only the silicon nitride film 44 has a reflective  
10 coating 45 formed thereon. As is illustrated in FIG. 7  
11 the deformable beams 48 are coplanar in their undeformed  
12 state and lie close to one another so that together they  
13 provide a substantially flat reflective surface. The  
14 beams 48 are, however, formed with a neck 50 at either  
15 end, which is off-center of the longitudinal center line  
16 of each of the beams 48.

17 When a uniformly distributed force, as a result of an  
18 applied voltage for example, is applied to the beams 48  
19 the resultant force  $F$ , for each beam 48, will act at the  
20 geometric center 52 of that beam. As each resultant force  
21  $F$  is off-set from the axis of rotation 54 (which coincides  
22 with the centerline of each neck 50), a moment of rotation  
23 or torque is applied to each beam 48 which results in a  
24 rotation of each beam 48 about its axis 54 to the position  
25 48' indicated in broken lines. This is known as "blazing"  
26 a diffraction grating.

27 As can be seen from FIG. 8, the reflective planes 56  
28 of the beams 48 remain parallel to each other even in this  
29 "blazed" configuration and therefore, the grating  
30 amplitude  $d$  is the perpendicular distance between the  
31 reflective surfaces of adjacent beams. This "blazed"  
32 grating will operate to diffract light in the same manner  
33 as a sawtooth grating.

34 Although not illustrated in any of FIGS. 1 to 8, it  
35 will be apparent that a deformable diffraction grating can  
36 be constructed in which, in its undeformed state, all the  
37 reflective elements are in the form of movable beam  
38 elements arranged parallel, adjacent and coplanar with  
39 each other. In this type of grating not only the grating



1 amplitude (i.e., the perpendicular distance between  
2 adjacent reflective surfaces) can be varied but also the  
3 average height of all the reflective surfaces can be  
4 changed by moving all the beams relative to a fixed datum.  
5 This arrangement has the advantage that both the amplitude  
6 and the phase of the reflected/diffracted light can be  
7 modulated.

8 The electrical, optical and mechanical  
9 characteristics of a number of modulators, similar in  
10 design to the modulator illustrated with reference to  
11 FIGS. 1 to 4 but of different dimensions were investigated  
12 by using a Helium Neon laser (of 633 nm wavelength)  
13 focused to a spot size of  $36\mu\text{m}$  on the center portion of  
14 each modulator. This spot size is small enough so that  
15 the curvature of the beams in the region where the  
16 modulator was illuminated can be neglected, but is large  
17 enough to allow the optical wave to be regarded as a plane  
18 wave and covering enough grating periods to give good  
19 separation between the zero and first order diffraction  
20 modes resulting from the operation of the grating. It was  
21 discovered that grating periods of (i.e.) the distance  
22 between the centerlines of two adjacent beams in the  
23 grating, 2,3 and  $4\mu\text{m}$  and a wavelength of 633 nm resulted  
24 in first order diffraction angles of  $18^\circ$ ,  $14^\circ$  and  $9^\circ$   
25 respectively.

26 One of these first order diffracted light beams was  
27 produced by using a  $120\mu\text{m}$ -long grating modulator with 1.5  
28  $\mu\text{m}$ -wide beams at atmospheric pressure together with a HeNe  
29 light beam modulated at a bit rate of 500 kHz. detected by  
30 a low-noise photoreceiver and viewed on an oscilloscope.  
31 The resulting display screen 30 of the oscilloscope is  
32 illustrated in FIG. 9.

33 However, before proceeding with a discussion of the  
34 features illustrated in this figure, the resonant  
35 frequency of the grating elements should first be  
36 considered.

37 The resonant frequency of the mechanical structure of  
38 the grating of the invention was measured by driving the  
39 deformable grating modulator with a step function and

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1 observing the ringing frequency. The area of the aluminum  
2 on the deformable grating modulator is roughly  $0.2 \text{ cm}^2$ ,  
3 which corresponds to an RC limited 3-dB bandwidth of 1 MHz  
4 with roughly 100 ohms of series resistance. This large  
5 RC time constant slowed down the step function, however,  
6 enough power existed at the resonant frequency to excite  
7 vibrations, even in the shorter beams. Although the  
8 ringing could be observed in normal atmosphere, the Q-  
9 factor was too low (approximately 1.5) for accurate  
10 measurements, so the measurements were made at a pressure  
11 of 150 mbar. At this pressure, the Q-factor rose to 8.6,  
12 demonstrating that air resistance is the major damping  
13 mechanism, for a grating of this nature, in a normal  
14 atmosphere.

15 Nonetheless, it was found that due to the high  
16 tensile stress in the beams, tension is the dominant  
17 restoring force, and the beams could therefore be modeled  
18 as vibrating strings. When this was done and the measured  
19 and theoretically predicted resonance frequencies  
20 compared, it was found that the theory is in good  
21 agreement with the experimental values, particularly when  
22 considering the uncertainty in tensile stress and density  
23 of the beams. As it is known that the bandwidth of forced  
24 vibrations of a mechanical structure is simply related to  
25 the resonance frequency and Q-factor, a Q-factor of 1.5  
26 yields a 1.5 dB bandwidth of the deformable grating  
27 modulator 1.4 times larger than the resonance frequency.  
28 The range of bandwidths for these gratings is therefore  
29 from 1.8 MHz for the deformable grating modulator with 120  
30  $\mu\text{m}$  beams to 6.1 MHz for the deformable grating modulator  
31 with 40  $\mu\text{m}$  beams.

32 Returning now to FIG. 9, it should be noted that with  
33 an applied voltage swing of 3 V, a contrast of 16dB for  
34 the 120  $\mu\text{m}$ -long bridges could be observed. Here the term  
35 "modulation depth" is taken to mean the ratio of the  
36 change in optical intensity to peak intensity.

37 The input (lower trace 62) on the screen 60  
38 represents a pseudo-random bit stream switching between 0  
39 and -2.7 V across a set of grating devices on a 1 cm by 1

1 cm die. The observed switching transient with an initial  
2 fast part followed by a RC dominated part, is caused by  
3 the series resistance of the deformable grating modulator,  
4 which is comparable to a 50 ohm source resistance.

5 The output (upper trace 64) on the screen corresponds  
6 to the optical output of a low-noise photoreceiver  
7 detecting the first diffraction order of the grating used.  
8 The output (upper trace 64) from the deformable grating is  
9 high when the beams are relaxed and low when the beams are  
10 deflected. Ringing is observed only after the rising  
11 transient, because of the quadratic dependence of the  
12 electro-static force on the voltage (during switching from  
13 a voltage of -2.7 V to 0 V, the initial, faster part of  
14 the charging of the capacitor corresponds to a larger  
15 change in electro-static force, than when switching the  
16 opposite way). This ringing in the received signal  
17 indicates a decay close to critical damping.

18 Furthermore, it was found that because the  
19 capacitance increases as the beams are pulled toward the  
20 substrate, the voltage needed for a certain deflection is  
21 not a monotonically increasing function of this  
22 deflection. At a certain applied voltage condition, an  
23 incremental increase in the applied voltage causes the  
24 beams to be pulled spontaneously to the substrate (to  
25 latch) and this voltage is known as the "switching  
26 voltage" of the modulator. The switching voltage was  
27 found to be 3.2 V for gratings with 120  $\mu\text{m}$  long beams and,  
28 if it is assumed that tension dominates the restoring  
29 forces, the switching voltage is inversely proportional to  
30 the beam length and therefore, the predicted switching  
31 voltage for 40  $\mu\text{m}$  long beams will be 9.6 V.

32 The importance of the switching voltage is that below  
33 this voltage, the deformable grating modulator can be  
34 operated in an analog fashion, however, if a voltage  
35 greater than the switching voltage is applied to the  
36 modulator it acts in a digital manner. Nonetheless, it is  
37 important to note that operating the modulator to the  
38 point of contact is desirable from an applications point  
39 of view, because as discussed above when the beams are

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1 deflected electrostatically, an instability exists once  
2 the beam deflection goes beyond the halfway point. This  
3 results in hysteretic behavior which will "latch" the beam  
4 in the down position. This latching feature gives the  
5 modulator the advantages of an active matrix design  
6 without the need for active components. A further  
7 advantage of this latching feature is that once the beam  
8 has "latched" it requires only a very small "holding  
9 voltage", much smaller than the original applied voltage,  
10 to keep the beam in its latched configuration. This  
11 feature is particularly valuable in low power applications  
12 where efficient use of available power is very important.

13 Finally, it was discovered that when the beams of the  
14 modulators are brought into contact with the substrate  
15 they could stick. This can be solved by adding small  
16 ridges below the beams to reduce the contact area between  
17 the beams and the substrate and thereby reduce the  
18 sticking problem.

19 The use of the modulator of this invention in  
20 displays requires high yield integration of individual  
21 modulator elements into 2-D arrays such as that  
22 illustrated in FIG. 10 which shows a plurality of grating  
23 modulators which can be used to provide a gray-scale  
24 operation. Each of the individual modulators 66, 68, 70,  
25 72 consist of a number of beams and gray-scale can be  
26 obtained by addressing each modulator in a binary-weighted  
27 manner. The hysteresis characteristic for latching (as  
28 described above) can be used to provide gray-scale  
29 variation without analog control of the voltage supplied  
30 to individual grating modulator elements.

31 In FIG. 11 the use of the grating, in combination  
32 with other gratings, for modulating white light to produce  
33 colored light is illustrated. This approach takes  
34 advantage of the ability of a grating to separate a light  
35 spectrum into its consistent colors. By constructing  
36 separate red, green and blue modulation elements each with  
37 a grating designed to diffract the appropriate color into  
38 an optical system, a color display which is white light

1 illuminated can be achieved. This approach is attractive  
2 for large area projection displays.

3 In summary, the reflective, deformable grating light  
4 modulator of this invention is a device which exhibits  
5 high resolution (40 by 40  $\mu\text{m}^2$  to 100  $\mu\text{m}^2$ ); high response  
6 times/large bandwidth (2 to 6 MHz); high contrast ratio  
7 (close to 100% modulation with a 3V switching voltage); is  
8 polarization independent and easy to use. This device  
9 also has tolerance for high optical power, has good  
10 optical throughput, is simple to manufacture, CMOS  
11 compatible, and has application in a wide range of fields  
12 including use as an SLM and with fiber optic technology.

13 Although the present invention has been described  
14 above in terms of specific embodiments, it is anticipated  
15 that alterations and modifications thereof will no doubt  
16 become apparent to those skilled in the art. It is  
17 therefore intended that the following claims be  
18 interpreted as covering all such alterations and  
19 modifications as fall within the true spirit and scope of  
20 the invention.

21 What is claimed is:

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CLAIMS

1 1. A modulator for modulating incident rays of light,  
2 the modulator comprising:

3 a plurality of equally spaced apart beam elements,  
4 each including a light reflective planar surface, the  
5 elements being arranged parallel to each other and with  
6 the light reflective surfaces of the beam elements being  
7 parallel to each other;

8 means for supporting the beam elements in relation to  
9 one another; and

10 means for moving the beam elements relative to one  
11 another between a first configuration wherein the  
12 modulator acts to reflect the incident rays of light as a  
13 plane mirror, and a second configuration wherein the  
14 modulator diffracts the incident rays of light as they are  
15 reflected therefrom.

1 2. A modulator as recited in claim 1, wherein the light  
2 reflective surfaces of the beam elements are parallel to  
3 each other in both the first and the second  
4 configurations.

1 3. A modulator as recited in claim 2, wherein the  
2 perpendicular spacing between the reflective surfaces of  
3 adjacent beam elements is equal to  $m/4$  times the  
4 wavelength of the incident rays of light, wherein  $m$  = an  
5 even whole number or zero when the beam elements are in  
6 the first configuration and  $m$  = an odd number when the  
7 beam elements are in the second configuration.

1 4. A modulator as recited in claim 3, wherein the means  
2 for moving the beam elements operates to rotate the beam  
3 elements when moving them relative to one another.

1 5. A modulator as recited in claim 3, wherein alternate  
2 beam elements are fixed relative to the support means.

1 6. A modulator as recited in claim 1, wherein the means  
2 for applying force to the beams comprises means for  
3 applying an electrostatic force to the beam elements.

1 7. A modulator as recited in claim 6, wherein the  
2 reflective surfaces are formed by metallic layers.

1 8. A modulator as recited in claim 7, wherein the means  
2 for applying electrostatic force includes the metallic  
3 layers.

1 9. A modulator as recited in claim 3, wherein the planar  
2 reflective surfaces of the beam elements are equal in  
3 dimensions and are substantially rectangular in plan.

1 10. A modulator as recited in claim 4, wherein the beam  
2 elements are resilient.

1 11. A modulator for modulating a beam of incident light,  
2 the modulator comprising;

3 a planar light reflective surface;

4 a deformable grating having a planar light reflective  
5 surface, the deformable grating being arranged with its  
6 reflective surface being parallel to and spaced from the  
7 planar reflective surfaces; and

8 means for moving the grating towards the planar  
9 reflective surface while at the same time maintaining the  
10 reflective surface of the grating substantially parallel  
11 to the planar reflective surface;

12 whereby, when the perpendicular spacing between the  
13 respective light reflective surfaces is equal to  $m/4$  times  
14 the wavelength of the incident light and  $m$  = an even whole  
15 number or zero the modulator acts to reflect the incident  
16 light as a plane mirror and when  $m$  = an odd whole number  
17 the modulator diffracts the incident light as it reflects  
18 it, thereby providing the modulation of the beam of light.

1 12. A modulator as recited in claim 11, wherein the  
2 grating comprises a plurality of equally sized and equally  
3 spaced apart parallel rectangular beam elements.

1 13. A modulator as recited in claim 12, wherein the  
2 spacing between each of the beam elements is substantially  
3 equal to the transverse width of each of the beam  
4 elements.

1 14. A modulator as recited in claim 13, wherein the  
2 spacing between the planar reflective surface and the  
3 reflective surface of the deformable grating is equal to  
4 half the wavelength of the beam of incident light.

1 15. A modulator as recited in claim 14, wherein the means  
2 for moving the grating towards the planar reflective  
3 surface comprises means for applying an electrostatic  
4 force between the planar reflective surface and the  
5 reflective surface of the grating.

1 16. A modulator as recited in claim 15, wherein the  
2 thickness of each beam element is equal to half the  
3 spacing between the two reflective surfaces.

1 17. A modulator as recited in claim 12 wherein the  
2 grating comprises a deformable resilient material.

1 18. A method of modulating a ray of light, comprising the  
2 steps of:

3 causing the ray to impinge on a plurality of equally  
4 spaced apart beam elements, each including a light  
5 reflective planar surface, the elements being arranged  
6 parallel to each other and with the light reflective  
7 surfaces of the beam elements being parallel to each  
8 other; and

9 moving the beam elements relative to one another  
10 between a first configuration wherein the modulator acts  
11 to reflect the incident rays of light as a plane mirror,  
12 and a second configuration wherein the modulator diffracts



13 the incident rays of light as they are reflected  
14 therefrom.

1 19. A method of modulating a ray of light as recited in  
2 claim 18, wherein the beam elements are moved to cause the  
3 perpendicular spacing between the reflective surfaces of  
4 adjacent beam elements to be equal to  $m/4$  times the  
5 wavelength of the incident rays of light, wherein  $m$  = an  
6 even whole number or zero when the beam elements are in  
7 the first configuration and  $m$  = an odd number when the  
8 beam elements are in the second configuration.

1 20. A method as recited in claim 19, wherein the  
2 thickness of each beam element is equal to half the  
3 spacing between the two reflective surfaces.

1 21. A method of modulating a ray of light as recited in  
2 claim 20, wherein the beam elements are caused to move  
3 relative to one another by applying an electrostatic force  
4 to the elements.

1 22. A modulator for modulating incident rays of light,  
2 the modulator comprising a plurality of elements arranged  
3 to act in concert to modulate the rays by means of  
4 diffraction, each element including:

5 a plurality of equally spaced apart beam elements,  
6 each including a light reflective planar surface, the  
7 elements being arranged parallel to each other and with  
8 the light reflective surfaces of the beam elements being  
9 parallel to each other;

10 means for supporting the beam elements in relation to  
11 one another; and

12 means for moving the beam elements relative to one  
13 another between a first configuration wherein the  
14 modulator acts to reflect the incident rays of light as a  
15 plane mirror, and a second configuration wherein the  
16 modulator diffracts the incident rays of light as they are  
17 reflected therefrom.

1 23. A modulator as recited in claim 22, wherein the light  
2 reflective surfaces of the beam elements are parallel to  
3 each other in both the first and the second  
4 configurations.

1 24. A modulator as recited in claim 23, wherein the  
2 perpendicular spacing between the reflective surfaces of  
3 adjacent beam elements is equal to  $m/4$  times the  
4 wavelength of the incident rays of light, wherein  $m$  = an  
5 even whole number or zero when the beam elements are in  
6 the first configuration and  $m$  = an odd number when the  
7 beam elements are in the second configuration.

1 25. A modulator as recited in claim 24, wherein the means  
2 for moving the beam elements operates to rotate the beam  
3 elements when moving them relative to one another.

1 26. A modulator as recited in claim 25, wherein alternate  
2 beam elements are fixed relative to the support means.

1 27. A modulator as recited in claim 4, wherein the means  
2 for moving the beam elements comprises means for applying  
3 an electrostatic force between the planar reflective  
4 surface and the reflective surface of the grating.

1 28. A modulator as recited in claim 27 wherein the beam  
2 elements comprise a deformable resilient material.



Fig. 1(a)

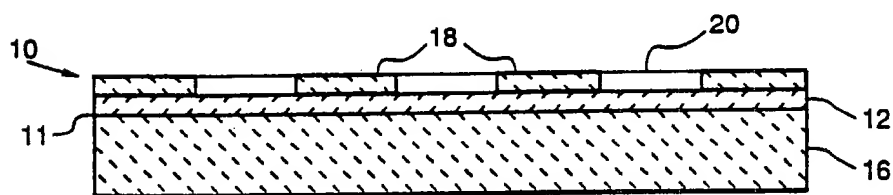


Fig. 1(b)

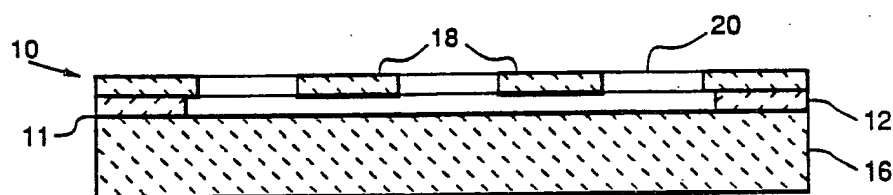


Fig. 1(c)

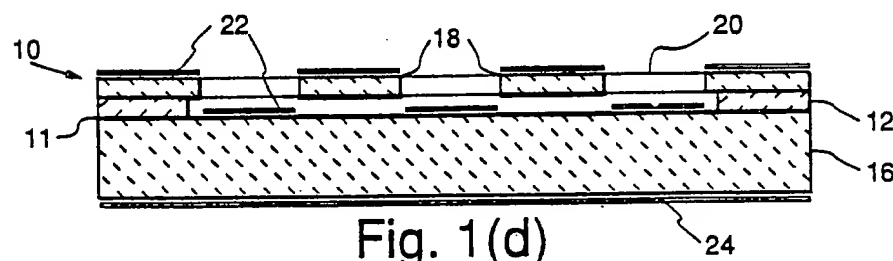


Fig. 1(d)



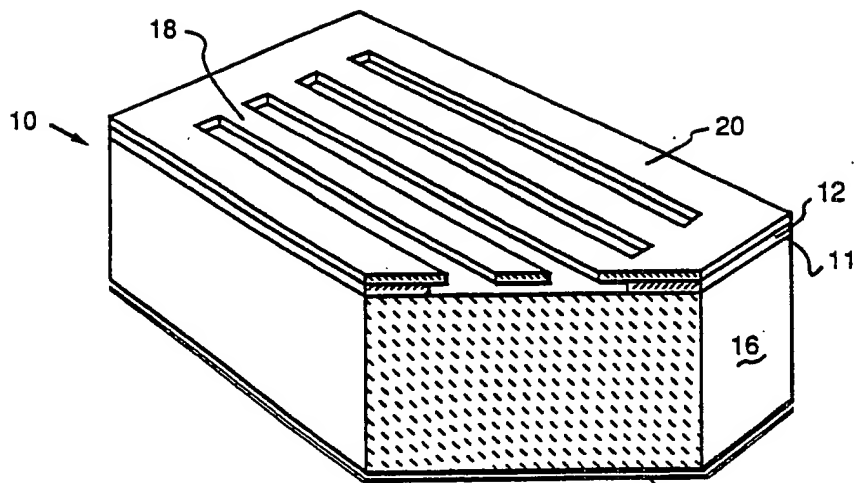


Fig. 2

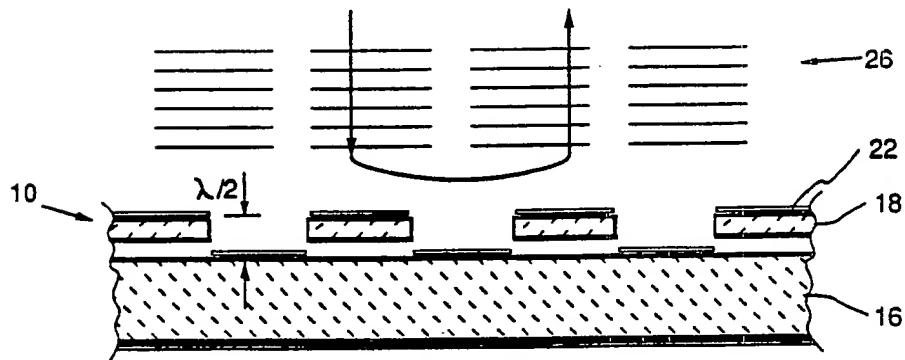


Fig. 3

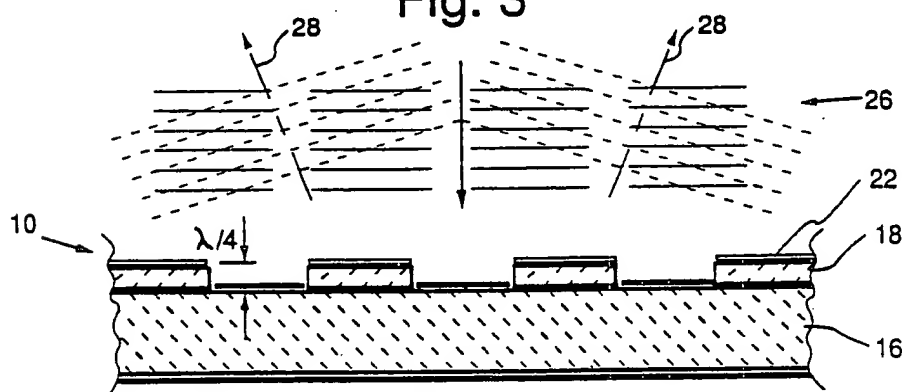
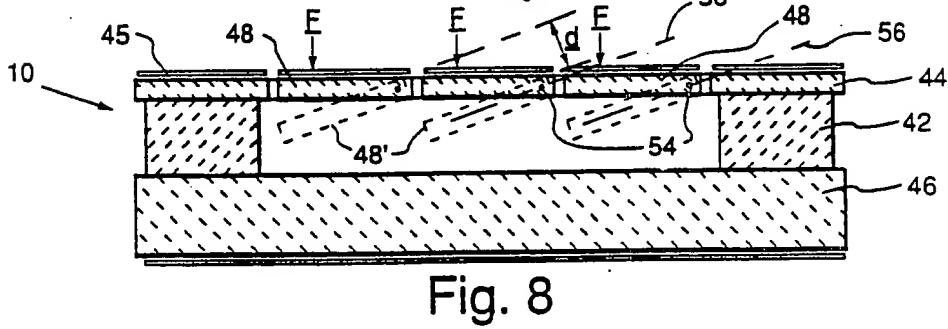
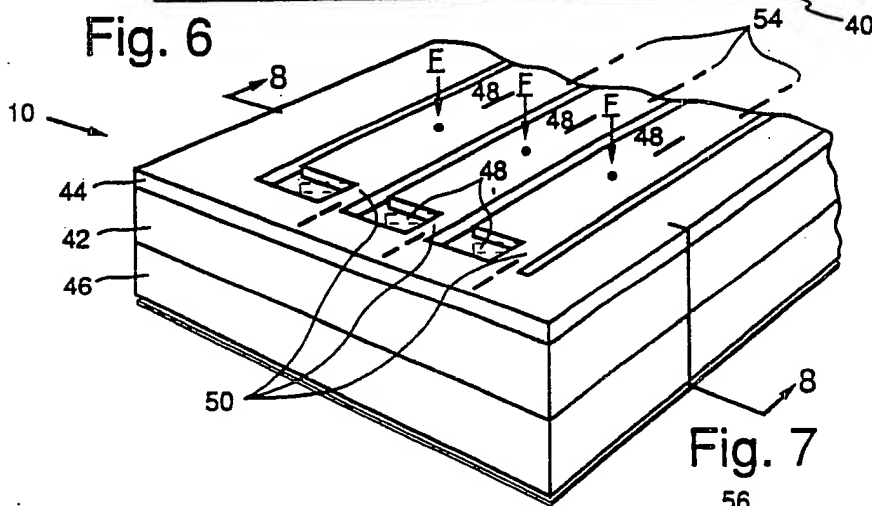
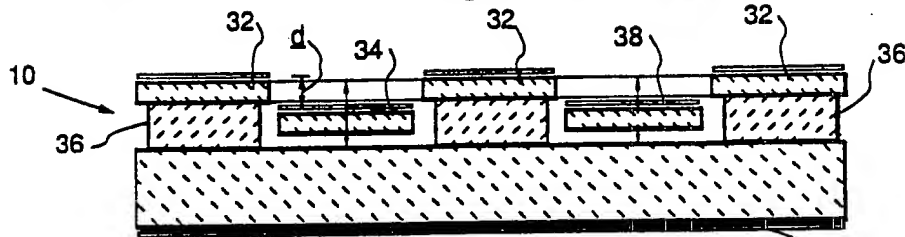
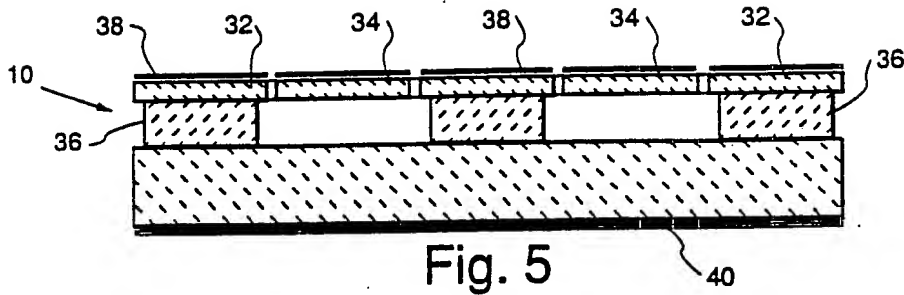


Fig. 4









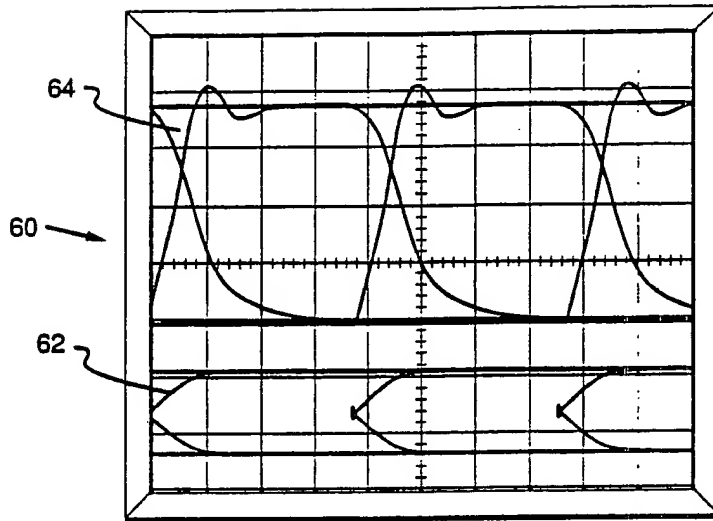


Fig. 9

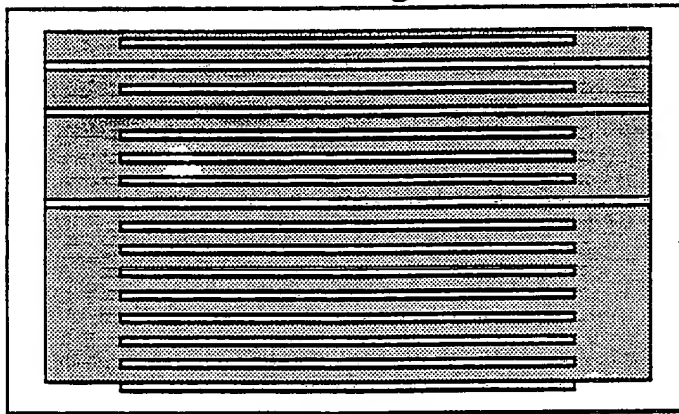


Fig. 10

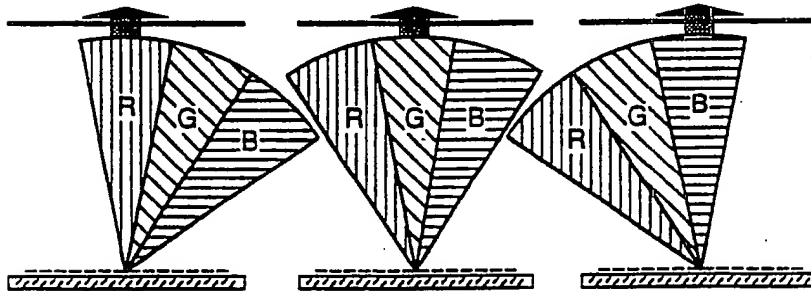


Fig. 11

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